



Dr. Katz at the University of North Carolina led the project in collaboration with Dr. Pearlstein and Dr. Guenther (Duke University and The Free Electron Laboratory Program). A one year contract (ICN# FA9550-06-1-0437), starting July 2006, was established between the Air Force Office of Scientific Research and the University of North Carolina at Chapel Hill. A six month no cost extension of the grant was approved and data collection was completed December 2007 on schedule. Data analysis was completed January 2008 and the final report was provided March 2008.

#### Project Productivity Summary

The specific aims for this project were met and a number of tangible results arose from the work. The work was presented at three national and one regional military/scientific conference and the work was accepted for publication in a high impact, peer reviewed scientific journal. Most importantly, the results of this study were enthusiastically reviewed by experienced battlefield surgeons who plan to evaluate the medical application of infrared imaging in Iraq this spring.

The central hypothesis for the present proposal was that certain traumatic injuries produce unique skin temperature signatures that can be quantified and automated for rapid identification with infrared (IR) imaging. The proposed effort builds on a foundation of past Army investment and University of North Carolina's extensive experience in IR imaging of traumatic injuries to achieve the following specific aims:

#### Specific aims

1. To determine the efficacy of passive IR imaging in diagnosing life-threatening pneumothoraces and related pulmonary injuries.
2. To determine the efficacy of passive IR imaging in diagnosing limb/life-threatening traumatic injuries such as compartment syndrome.

The proposed effort addressed several of the critical issues including: (1) collecting a base of patient images from which skin temperature signatures of life or limb threatening conditions can be identified; (2) refining existing methods for visualizing IR radiometric images; and (3) facilitating the introduction of this technology into military medical practice (collaborative effort with other military branches). The lessons learned from the proposed work will also facilitate future efforts for using IR imaging for diagnosing other acute battlefield injuries.

#### Summary Results:

1. 305 critically ill trauma patients were screened for the study.
2. 200 patients were enrolled in the study.
3. IR depth of field, camera lens, capture angle and distance from patient established.
4. Surface temperature of the chest and lower extremities were measured.
5. Surface temperature lower on side with pneumothorax.
6. IR technology was insufficient to discriminate patients with pneumothorax



7. Surface temperature lower in limb that developed compartment syndrome.
8. IR technology promising for early diagnosis of compartment syndrome.

### **Pneumothorax objective**

Rationale: A pneumothorax (collapsed lung) can occur during battle from either blunt or penetrating trauma. Pneumothoraces are relatively easy to diagnose in a quiet and safe environment if there is access to X-ray equipment. However, the battlefield can limit the ability to recognize such injuries because of lack of portable equipment, noise, poor lighting and environmental dangers. Failure to diagnosis a pneumothorax can lead to death within seconds to minutes. A simple medical procedure, which can be performed in the field in a matter of seconds by a medic with minimal experience and practically no equipment, can be lifesaving if the pneumothorax is rapidly recognized. Therefore, it would be beneficial to have a simple to operate, portable technology capable of assisting with the diagnosis of this life threatening traumatic injury in the battlefield. Infrared imaging may be a technology that can assist with the diagnosis of a pneumothorax since the lung is a source of heat that radiates to the chest surface. A collapsed lung would be expected to create a decrease in surface temperature when compared to the unaffected side. Advances in infrared technology now provide the resolution necessary to detect these subtle changes in chest temperature produced by a pneumothorax and may aid in the rapid diagnosis and stabilization of soldiers with such injuries.

### **Results:**

Surface temperature on the left side of the chest with a pneumothorax ( $32.78 \pm 2.72^{\circ}\text{C}$ ) was lower compared to controls ( $33.25 \pm 2.01^{\circ}\text{C}$ ) with no pneumothoraces. However, the difference was not statistically significant unless the pneumothorax required a chest tube ( $32.01 \pm 2.72^{\circ}\text{C}$  ANOVA  $p < 0.05$ ). Surface temperature on the right side of the chest with a pneumothorax ( $33.18 \pm 1.56^{\circ}\text{C}$ ) was lower compared to controls ( $33.21 \pm 2^{\circ}\text{C}$ ) with no pneumothoraces. These values were not statistically significant even if the pneumothorax required a chest tube ( $33.05 \pm 2.01^{\circ}\text{C}$ ). Logistic regression revealed that IR was poor for discriminating patients with pneumothoraces.

A number of limitations to image analysis were prospectively identified. The greatest challenge was analyzing images with artifacts (such as EKG leads) covering a significant portion of the chest surface. The data was prospectively collected and arranged so that images without artifacts (termed pristine) could also be analyzed. However, the above results did not change in this small number of patients. Advanced image analysis of all patients is planned to determine if a reliable methodology can be developed to improve the sensitivity and specificity of IR to discriminate pneumothoraces. IR imaging also did a poor job discriminating pneumothoraces for individual patients when their contralateral (non-pneumothorax) side of the chest was used for comparison.

### **Compartment Syndrome Objective**

Rationale: Compartment syndrome is produced by blunt or penetrating trauma to a limb resulting in severe internal swelling and subsequent blockage of blood flow to the involved extremity. Patients with multiple injuries can often have these types of injuries that go undetected for hours because of other distracting injuries. In addition, invasive

procedures and specialized equipment is currently required to confirm the diagnosis of compartment syndrome. Failure to recognize such injuries within the 3-6 hours after onset can lead to the need for amputation of the involved limb or complex and painful reconstructive surgery if no therapy is initiated. Failure to make the early diagnosis of compartment syndrome can also lead to multiorgan system failure and death. Therefore, new methods to recognize such injuries on the battlefield and during evacuation may lead to limb and life saving surgery. Detection of compartment syndrome is especially amendable to infrared imaging because the involved limb becomes cooler than the non traumatized limb before there is any clinical evidence (decreased arterial pulse or paralysis) of compartment syndrome. Once clinical signs of compartment syndrome are present, the likelihood of amputation or extensive reconstructive surgery increase exponentially, thus time to diagnosis is critical. Infrared imaging may be capable of immediate detection of compartment syndrome on the battlefield and reduction in the incidence of amputation and death.

## Results

There is a significant decrease in surface temperature in limbs that develop compartment syndrome. Infrared imaging performed on trauma patients in the Emergency Department was able to discriminate limbs that developed compartment syndrome. The results of this study are summarized in the manuscript entitled "Infrared Imaging for Detection of Acute Compartment Syndrome of the Limbs" accepted for publication to Critical Care Medicine January 27 2008 (preprint version attached). Table 1 summarizes outcome in patients who met IR criteria for developing compartment syndrome on presentation to the ED, but were not diagnosed with compartment syndrome until later in their hospitalization.

## Compartment Syndrome Outcome

<u>CS</u>	<u>Surgery</u>	<u>Injury Mechanism and pattern</u>	<u>Limb Outcome</u>
Left	20	MC, TBI, left tibia/fibula FX PTX, pulmonary contusion, liver laceration	left AKA
Left	7	MVC, left femur FX, left tibia FX, PTX, flail chest, pulmonary contusion	limp, skin necrosis
Left	6	MVC, left fibular FX left acetabular fracture	limp
Left	6	MVC, left leg contusion pulmonary contusion,	limp
Right	8	MVC, TBI, right tibia/fibula FX left femur FX, left tibia FX, pelvic FX	right AKA



Right	6	MC, TBI, right tibia/fibula FX pulmonary contusion and PTX	non healing ulcers right leg
Right	4	Assault with bat, TBI, leg contusion	functional
Bilateral	26	PVC, TBI, tibia/fibula FX (B)	severe left leg contracture
Bilateral	9	PVC, TBI, femur FX (B), PTX shock, spleen laceration	AKA (B)
Bilateral	3	Industrial crush, TBI, right femur FX	functional
Bilateral	3	Fall, tibia/fibula FX (B)	functional

Table 1. Demographics of patients that developed compartment syndrome. Surgery represents approximate time (hours) from injury to operative intervention. Abbreviations; CS (compartment syndrome), FX (fracture), PVC (pedestrian struck by a car), MVC (motor vehicle crash), MC (motorcycle crash), TBI (traumatic brain injury), PTX (pneumothorax), AKA (above the knee amputation) and (B) (bilateral).

Figure 1 illustrates the excellent ability of IR to discriminate patients who develop compartment syndrome.

## Logistic Fit of Compartment Syndrome Diagnosis by Thigh-Foot Index (TFI)

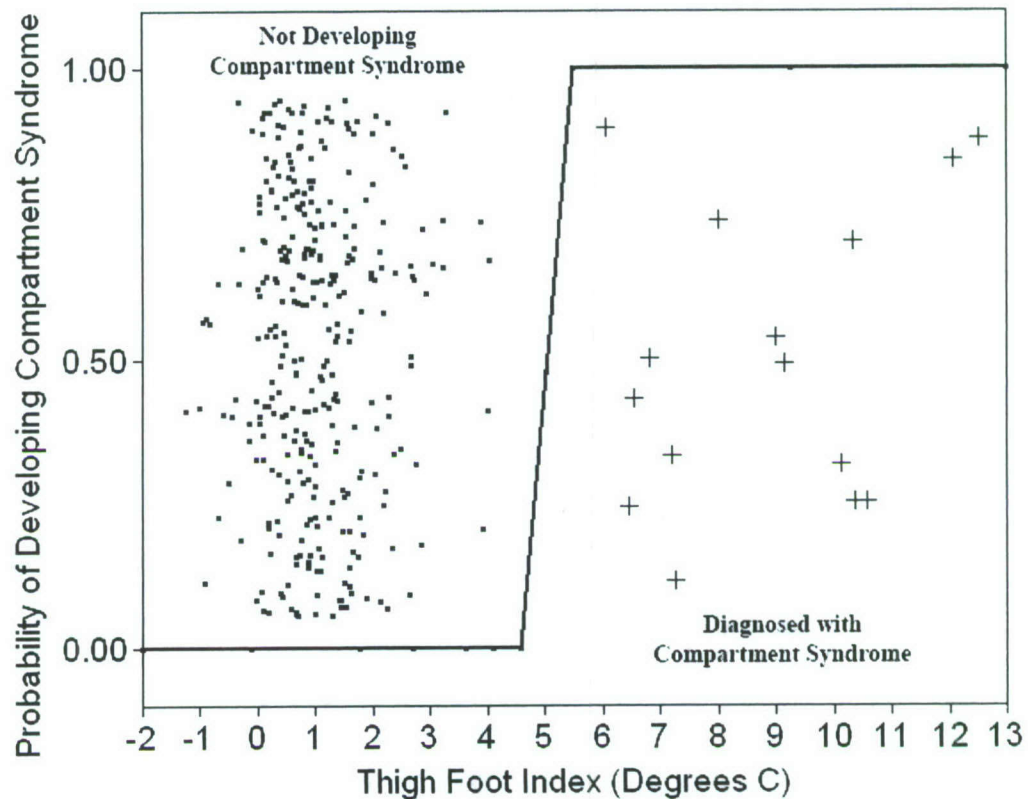


Figure 1. The figure shows the maximum likelihood probability curve (solid line) for the compartment syndrome diagnosis derived from fitting the Thigh-Foot Index (TFI) data to a nominal logistics model. TFI is the average temperature of the anterior thigh surface minus the average temperature of the anterior foot. The Y axis represents the likelihood ratio (0-1) of the diagnosis of compartment syndrome and applies only to the probability curve, not to the scatterplot points. Scatter points designated with dots (·) indicate TFI measurements for which compartment syndrome was not observed; points designated with crosses (+) denote TFI measurements for which a diagnosis of compartment syndrome occurred. Scatter plot of the TFI observed in the legs that develop compartment syndrome are all below the logistics fit line, completely discriminated from the TFI found in the legs that do not develop compartment syndrome.

In conclusion, IR imaging holds great promise as an inexpensive, non-invasive and portable technology for the early detection of compartment syndrome. The technology is now ready for evaluation in the less controlled environment of the battlefield. If this technology proves effective in this environment, it holds great potential for reducing morbidity and mortality in soldiers at risk for developing compartment syndrome.



Title Page

Infrared Imaging of Trauma Patients for Detection of Acute Compartment Syndrome of the Leg

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## Abstract

Early compartment syndrome is difficult to diagnose and a delay in the diagnosis can result in amputation or death. **Objective:** Explore the potential of infrared imaging, a portable and non-invasive technology, for detecting compartment syndrome in the legs of patients with multiple trauma. We hypothesized that development of compartment syndrome is associated with a reduction in surface temperature in the involved leg and the temperature reduction can be detected by infrared imaging. **Design:** Observational clinical study. Setting: Level I trauma center between July 2006 and July 2007. Patients: trauma patients presenting to the ED. **Patient interventions:** Average temperature of the anterior surface of the proximal and distal region of each leg was measured in the Emergency Department with a radiometrically calibrated 320 x 240 uncooled microbolometer Infrared Camera. **Measurements:** The difference in surface temperature between the thigh and foot regions (Thigh-Foot Index (TFI)) of the legs in trauma patients was determined by investigators blinded to injury pattern using thermographic image analysis software. The diagnosis of compartment syndrome was made intraoperatively. **Main Results:** Thermographic images from 164 patients were analyzed. Eleven patients developed compartment syndrome and four of those patients had bilateral compartment syndrome. Legs that developed compartment syndrome had a greater difference in proximal versus distal surface temperature ( $8.80 \pm 2.05^{\circ}\text{C}$ ) versus legs without compartment syndrome ( $1.22 \pm 0.88^{\circ}\text{C}$ ) (ANOVA  $p < 0.01$ ). Patients who developed unilateral compartment syndrome had a greater proximal versus distal temperature difference in the leg with ( $8.57 \pm 2.37^{\circ}\text{C}$ ) versus the contralateral leg without development of compartment syndrome ( $1.80 \pm 1.60^{\circ}\text{C}$ ) (ANOVA  $p < 0.01$ ).



**Conclusion:** Infrared imaging detected a difference in surface temperature between the proximal and distal leg of patients who developed compartment syndrome. This technology holds promise as a supportive tool for the early detection of acute compartment syndrome in trauma patients.

## **Introduction**

Compartment syndrome can be difficult to diagnose, especially in patients with altered mental status or multiple trauma.[1] The diagnosis of compartment syndrome is usually a clinical diagnosis, although direct measurements of compartment pressures can support the diagnosis. There are disagreements on what pressure readings are diagnostic of compartment syndrome.[2] In addition, abnormal compartment pressures may occur in patients who do not develop compartment syndrome, further reducing the reliability of pressure measurements.[3]

Trauma with swelling of muscles within confined compartments, such as the legs, can produce elevated pressures and leg ischemia. [4, 5] The precise time from leg ischemia to muscle and nerve necrosis is unknown, but may occur as early as three hours after the onset of injury.[6, 7] Better methods are needed for the early diagnosis of compartment syndrome since delays in the diagnosis that occur with the current procedures are common and can result in permanent disability or death.[8-10]

The purpose of this study was to explore the potential of infrared imaging for detecting differences in surface temperatures in the legs of trauma patients who develop

compartment syndrome. Infrared imaging is a noninvasive method for measuring surface temperatures and a correlation exists between skin temperatures and limb blood flow. [5, 11-15]. Advances in the development of an uncooled camera, image resolution and software, now available at relatively low cost, make infrared imaging practical for medical applications.[16] Since compartment syndrome causes a decrease in leg blood flow we hypothesize that development of compartment syndrome is associated with a reduction in surface temperature in the involved leg.

## **Methods**

The study was approved by the Institutional Review Board of the University Of North Carolina School Of Medicine. Informed written consent was obtained from patients or their legal authorized representative. Research assistants were present in the ED 120 hours per week, including days, nights and weekends when trauma volume was heaviest based on the previous year's trauma registry. Patients were assessed for inclusion in the study if a research assistant was present during the trauma activation and the patient presented to the ED within four hours of injury onset and was 18 years of age or older. Patients were excluded from analysis if they were under age 18, declined consent, pregnant, sustained burns, no pulses in their legs, poor image quality or legs not exposed during resuscitation (Diagram 1). The criteria for trauma activation included respiratory difficulty, intubation, a systolic blood pressure less than 90mmHg, a heart rate less than 60 or above 110, penetrating head, neck chest or abdominal injuries or "any other injured patients at the ED attendings discretion."



Research assistants were undergraduate students who calibrated the camera before the patient's arrival and had no interactions with the patient or trauma team during the initial resuscitation or image capturing. Images were obtained during the patient's initial trauma resuscitation in the ED. The camera was secured above the patient and operated remotely so it would not interfere with care provided by the resuscitation team. The camera was aligned at the same angle and distance from patients (90cm above the hips). The images were captured with the L-Wave infrared camera (IRcameras Inc, Walpole, MA). The camera was a 320 x 240 array uncooled microbolometer, a radiometric instrument used for imaging long wave (8-14 micron) infrared emissions. The camera was radiometrically calibrated against an external blackbody reference source (Omega Engineering BB702, Stamford Connecticut) with an accuracy of  $\pm 0.5^{\circ}\text{C}$ .

Four research assistants, blinded to the patient's presentation, injury pattern and outcome analyzed the images at a later date. Patients who developed compartment syndrome were identified by review of medical records that reported fasciotomies with an intraoperative diagnosis of compartment syndrome. Patient outcomes were determined by review of medical records and discharge summaries.

For image analysis, the average temperature of the anterior surface of the thigh from the level of the mid thigh to just above the patella was designated the thigh region. The average anterior surface temperature from the distal lateral malleolus to toes was designated the foot region. The average temperature difference between the thigh and foot was designated the Thigh-Foot Index (TFI). These regions of interest, in addition to

the whole leg, were outlined by the research assistants using the Thermography Suite software (IRcameras Inc. Walpole, MA). The software then automatically converted the absorbed radiant heat within the defined regions of interest to temperature values.

### Statistics

The temperature data was expressed as means and standard deviations. A one-way analysis of variance was used to test the effect of compartment syndrome on the average temperature of the anterior surface temperature of the whole leg and the difference in temperature of the Thigh-Foot Index (TFI). An analysis of co-variance was performed to determine if blood pressure, shock, body temperature, lower extremity fractures or ambient temperature affected the temperature values. When a difference was detected the Bonferroni post hoc analysis was performed. A nominal logistic model and Chi Square analysis was used to determine whether the anterior leg surface temperature can discriminate the patients who developed compartment syndrome. An area under the receiver operator characteristic (ROC) curve was used to assess discrimination efficiency. Inter-rater reliability of image analysis measure of surface temperatures was determined with a two way mixed model of intraclass correlation coefficient. A Chi Square analysis was used to evaluate the difference in injury patterns between patients with and without compartment syndrome. Significance was set at a  $p < 0.05$ . Analysis was performed with SAS JMP statistical software version 7.

### Results

There were 200 hundred trauma alerts while research assistants were present in the ED. Thirty six patients were prospectively excluded, 2 before data collection because they



were found to be less than 18 years of age, 4 declined consent, 2 burns, 1 pulseless leg, 8 presenting greater than 4 hours after the injury, and 12 because their legs were not exposed during the resuscitation. An additional 7 patients were prospectively excluded because of poor image quality (lack of focus and patient alignment). None of these excluded patients developed compartment syndrome. Diagram 1 shows when the patients were excluded during the enrollment.

Table 1 shows group characteristics for the 11 patients developing compartment syndrome and the 153 patients included in the study who did not (the control group). The distribution of traumatic injuries was similar between groups except there was a higher incidence of lower extremity fractures in patients who developed compartment syndrome (Chi Square  $p < 0.001$ ). Patients who developed compartment syndrome sustained blunt trauma from either motor vehicle crashes 4/11 (36%), pedestrians struck by a car 2/11 (18%), motorcycle crashes 2/11 (18%), a witnessed crush injury 1/11 (9%), a fall 1/11 (9%), or assault 1/11 (9%). The mechanism of injury in the control group was motor vehicle crashes 74/153 (48%), falls 24/153 (16%), motorcycle crashes 19/153 (12%), pedestrians struck by a car 11/153 (7%), assaults 7/153 (5%), witnessed crush injury 2/153 (1%), or penetrating injuries from gunshot wounds or stabbings 16/153 (10%).

Eleven patients developed compartment syndrome, four of those with bilateral leg compartment syndrome, four with left leg compartment syndrome and three with right leg compartment syndrome. Table 2 shows the approximate time from injury to surgical

intervention, mechanism and distribution of injuries, and outcome of legs upon discharge from the hospital.

The average anterior surface temperature of legs in patients without compartment syndrome was  $31.86 \pm 1.99^{\circ}\text{C}$ . Image 1 is an example of a temperature signature and region of interest analysis of legs in a control patient in the emergency department without compartment syndrome. The average anterior surface temperature in legs that developed compartment syndrome ( $28.70 \pm 2.03^{\circ}\text{C}$ ) was significantly lower compared to controls (ANOVA  $p < 0.01$ ). Image 2 is an example of the temperature signature and region of interest in a patient in the emergency department who subsequently developed right leg compartment syndrome.

In patients who developed unilateral compartment syndrome, the average temperature on the anterior surface of legs that developed compartment syndrome ( $28.95 \pm 2.20^{\circ}\text{C}$ ) was significantly lower than the contralateral legs ( $32.75 \pm 2.29^{\circ}\text{C}$ ) without compartment syndrome (ANOVA  $p < 0.01$ ). The average temperature on the anterior surface of legs in patients who developed bilateral compartment syndrome ( $28.47 \pm 1.80^{\circ}\text{C}$ ) was significantly lower than controls ( $31.86 \pm 1.99^{\circ}\text{C}$ ) (ANOVA  $p < 0.01$ ).

Thigh-Foot Index (TFI; difference between regional temperatures of the anterior surface of the thigh and foot) was greater in legs that developed compartment syndrome ( $8.80 \pm 2.05^{\circ}\text{C}$ ) compared with legs without compartment syndrome ( $1.22 \pm 0.88^{\circ}\text{C}$ ) (ANOVA  $p < 0.01$ ). In patients who developed unilateral compartment syndrome, TFI was greater in



the leg that developed compartment syndrome ( $8.57 \pm 2.37^{\circ}\text{C}$ ) versus the contralateral leg ( $1.80 \pm 1.60^{\circ}\text{C}$ ) (ANOVA  $p < 0.01$ ). In patients who developed bilateral compartment syndrome, TFI ( $9.01 \pm 1.52^{\circ}\text{C}$ ) was also significantly greater than controls ( $1.22 \pm 0.88^{\circ}\text{C}$ ) (ANOVA  $p < 0.01$ ). Image 3 provides an example of a patient in the emergency department who subsequently developed bilateral compartment syndrome of the legs that was analyzed with the TFI strategy.

Blood pressure, the presence of shock, body temperature, lower extremity fractures, and ambient temperature were not significant confounding variables for measure of surface temperatures (ANCOVA test). Four research assistants independently analyzed the images and the inter-rater reliability for the analysis of surface temperatures was excellent (correlation coefficient 0.98).

Temperature measurements were fit to a nominal logistics model to assess power to discriminate patients who developed compartment syndrome in the leg. TFI (figure 1), foot temperature, and whole leg temperature (data not shown) were all found to provide significant discrimination power ( $p < 0.0001$ ). Area under the receiver operating characteristic curve was assessed as a measure of discrimination efficiency. TFI and foot temperature were both found to have excellent discrimination ( $\text{AUC} = 1.0$  and  $\text{AUC} = 0.98$  respectively), the whole leg temperature provided moderate discrimination ( $\text{AUC} = 0.86$ ) and the thigh temperature alone provided poor discrimination ( $\text{AUC} = 0.54$ ) between patients who would and would not develop compartment syndrome.

## Discussion

The anterior surface temperature was lower in the legs of trauma patients that developed compartment syndrome. Infrared imaging was able to detect these temperature changes during the patient's initial trauma survey in the Emergency Department. The temperature pattern in legs that developed compartment syndrome was also unique. In legs that developed compartment syndrome, the differential temperature between the thigh and foot was markedly increased in comparison to controls. This unique temperature pattern, referred to here as the Thigh-Foot Index (TFI), provides a potential method as a supportive tool for early identification of compartment syndrome in trauma patients who sustain blunt trauma

There is no gold standard for the diagnosis of compartment syndrome. Serial physical exams assessing for pain, pallor, paresthesias, soft tissue swelling and pulses in awake patients is currently the standard for establishing the diagnosis of compartment syndrome, but many of these findings may not be present until late in the disease process when damage is irreversible.[4, 7, 17, 18] The physical exam is even less reliable in unconscious patients, a common occurrence in patients with multiple trauma.[8] Adjuvants such as invasive measures of compartment pressures are used to support the diagnosis, but these direct measures alone can not confirm that a patient will develop compartment syndrome and the need for surgical interventions.[3, 19] The results of this study suggest that infrared imaging holds potential as a non-invasive tool that at a minimum may raise suspicion for early compartment syndrome. Failure to consider the



diagnosis of compartment syndrome as well as some late physical manifestations of the disease process (such as loss of pulses) are common causes for the delayed diagnoses of compartment syndrome.[10, 17, 18] Delays in the diagnosis of compartment syndrome can lead to delays in treatment and poor outcome in as short as 4-8 hours [6, 7], further emphasizing the need for an early diagnostic tool for compartment syndrome.

Acute compartment syndrome of the leg is most commonly caused by high impact crush or blast injuries.[20, 21] These traumatic injuries create local tissue damage and swelling in lower leg compartments that are unable to accommodate the increasing pressures. The increasing compartment pressures collapse capillaries, lower arteriovenous pressure gradients and decrease blood flow locally and distal to the injury, resulting in tissue ischemia and necrosis. [4, 5] Since blood flow is the predominant source of heat in limbs [11, 22] and blood is supplied to the leg from a proximal source, it seemed a reasonable hypothesis to assume that temperatures would be lower in legs developing compartment syndrome, especially when comparing temperature proximal and distal to the injury. The results of this study and specifically the TFI temperature differences support this hypothesis. Prospective studies correlating TFI temperature differences with direct measure of compartment pressures are necessary to establish the utility of infrared imaging for the early diagnosis of compartment syndrome.

Trauma patients in this study were imaged within two minutes of arrival to the Emergency department stretcher and an average of approximately 90 minutes after the initial injury. That time period is well within the time frame required for leg salvage.[6,

7] Our outcomes results support the observation that delays in treatment negatively impact on outcome. However, the reasons for the delays were not evaluated in this study and require further investigation.

Infrared imaging is a safe, non-invasive, portable, relatively inexpensive technology that can be operated remotely. Remote operation of the camera allows for unobstructed access to the patient that is critical during the initial trauma resuscitation. The infrared camera is also capable of repeated measures and will be the focus of future research examining the correlation of surface temperatures with progression and resolution of leg swelling and compartment syndrome.

#### Limitations of the Study

Infrared imaging measures surface temperatures so clothing or blankets that cover the legs will interfere with temperature measurements. The protocol recognized this limitation and prospectively excluded patients that were not fully exposed during the resuscitation. Early in the study the research assistants noted that not all patients were being exposed and this was unexpected since residents and attending physicians that perform trauma resuscitations are trained in Advanced Trauma Life Support that requires full exposure of the patient during the primary resuscitation. The research assistants did not interfere with patient's resuscitation as trained. However, this important information was provided to the Director of Trauma and The Emergency Medicine Residency Director, and residents were provided with further education on the importance of fully



exposing patients during the primary resuscitation in order to minimize the chances of missing occult injuries.

All patients that developed compartment syndrome in this study sustained blunt trauma. There was a much higher incidence of lower extremity fractures in patients who developed compartment syndrome. However, no temperature anomalies were observed in fractured legs that did not develop compartment syndrome. Further study will be required to determine whether infrared imaging will be of utility for detecting development of compartment syndrome in patients from other causes.

Leg blood flow and compartment pressures were not measured in this study. Therefore, we are unable to determine what physiological responses caused the skin temperature changes in patients who developed compartment syndrome. In addition it is possible that other physiological changes such as alterations in autonomic function may have produced changes in the surface temperature in legs that developed compartment syndrome.[23] Despite these limitations, infrared imaging was able to discriminate legs that developed compartment syndrome.

An operative report of compartment syndrome is the most objective method available for making the diagnosis of compartment syndrome, although that method still has potential for bias. However, surgeons were not provided access to the images or results of the study. Finally, the diagnosis of compartment syndrome was made on chart review and not prospectively. As a result, the indications for deciding when to perform a fasciotomy

were not available for this study. Prospective studies are now being planned to evaluate the clinical impact of infrared imaging on detection of compartment syndrome.

## Conclusions

Infrared imaging detected a decrease in the anterior surface temperature of the whole leg of trauma patients that developed compartment syndrome after blunt trauma. These changes were noted early in the patient's hospital course. The Thigh-Foot Index (TFI) temperature was an excellent indicator for development of compartment syndrome in the legs. Infrared imaging is a non-invasive technology that holds promise as a supportive tool for the early detection of compartment syndrome in the legs of trauma patients that sustain blunt trauma.

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## References

1. Olson SA, Glasgow RR: Acute compartment syndrome in lower extremity musculoskeletal trauma. *J Am Acad Orthop Surg* 2005; 13:436-444
2. Janzing HM, Broos PL: Routine monitoring of compartment pressure in patients with tibial fractures: Beware of overtreatment! *Injury* 2001; 32:415-421
3. Prayson MJ, Chen JL, Hampers D, et al: Baseline compartment pressure measurements in isolated lower extremity fractures without clinical compartment syndrome. *J Trauma* 2006; 605:1037-1040
4. Mabee JR, Bostwick TL: Pathophysiology and mechanisms of compartment syndrome. *Orthopaedic Review* 1993; 222:175-181
5. Ashton H: The effect of increased tissue pressure on blood flow. *Clin Orthop Relat Res* 1975; 113:15-26

6. Vaillancourt C, Shrier I, Vandal A, et al: Acute compartment syndrome: How long before muscle necrosis occurs? *Cjem* 2004; 6:147-154
7. Whitesides TE, Heckman MM: Acute Compartment Syndrome: Update on Diagnosis and Treatment. *J Am Acad Orthop Surg* 1996; 4:209-218
8. Frink M, Klaus AK, Kuther G, et al: Long term results of compartment syndrome of the lower limb in polytraumatized patients. *Injury* 2007; 38:607-613
9. Heemskerk J, Kitslaar P: Acute compartment syndrome of the lower leg: retrospective study on prevalence, technique, and outcome of fasciotomies. *World J Surg* 2003; 27:744-747
10. Vaillancourt C, Shrier I, Falk M, et al: Quantifying delays in the recognition and management of acute compartment syndrome. *Cjem* 2001; 3:26-30
11. Forster RE, Ferris BG, Day R: The relationship between total heat exchange and blood flow in the hand at various ambient temperatures. *Am J Physiol* 1946; 146:600-609
12. Astrup A, Bulow J, Madsen J: Skin temperature and subcutaneous adipose blood flow in man. *Scand J Clin Lab Invest* 1980; 40:135-138
13. Jogestrand T, Berglund B: Estimation of digital circulation and its correlation to clinical signs of ischaemia--a comparative methodological study. *Clin Physiol Funct Imaging* 1983; 3:307-312
14. Nilsson AL: Blood flow, temperature, and heat loss of skin exposed to local radiative and convective cooling. *J Invest Dermatol* 1987; 88:586-593
15. Rubinstein EH, Sessler DI: Skin-surface temperature gradients correlate with fingertip blood flow in humans. *Anesthesiology* 1990; 73:541-545
16. Jones BF: A reappraisal of the use of infrared thermal image analysis in medicine. *IEEE Trans Med Imaging* 1998; 17:1019-1027
17. Matsen FA, Winkquist RA, Krugmire RB, Jr.: Diagnosis and management of compartmental syndromes. *J Bone Joint Surg Am* 1980; 62:286-291
18. Tiwari A, Haq AI, Myint F, et al: Acute compartment syndromes. *Brit J Surg* 2002; 89:397-412
19. White TO, Howell GE, Will EM, et al: Elevated intramuscular compartment pressures do not influence outcome after tibial fracture. *J Trauma* 2003; 55:1133-1138
20. Gonzalez D: Crush syndrome. *Crit care med* 2005; 33:S34-41
21. Kostler W, Strohm PC, Sudkamp NP: Acute compartment syndrome of the limb. *Injury* 2004; 35:1221-1227
22. Weinbaum S, Xu LX, Zhu L, et al: A new fundamental bioheat equation for muscle tissue: Part I--Blood perfusion term. *J Biomech Eng* 1997; 119:278-288
23. Baron R: Mechanistic and clinical aspects of complex regional pain syndrome (CRPS). *Novartis Found Symp* 2004; 261:220-233



## Inclusion and Exclusion of Patients in Study

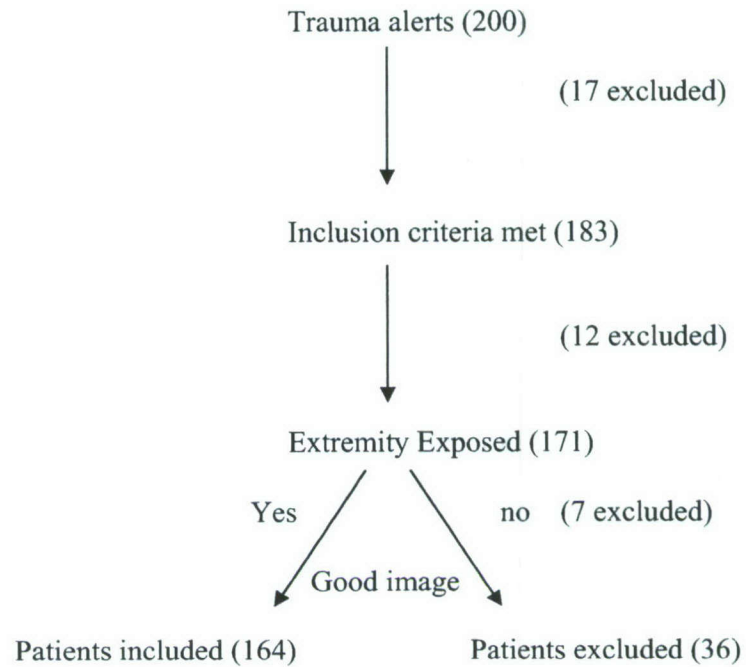


Diagram 1 Flow diagram showing when patients were entered or excluded from the study. Inclusion criteria included activation of a trauma alert, the injury occurred within four hours of presentation and the patient was 18 years of age or older. Patients were excluded from analysis if they were found to be under age 18 (2), pregnant (0), declined consent (4), burns (2), had no pulses in the legs (1), presented greater than 4 hours after the injury (8) or if the extremities were not exposed during resuscitation (12). An additional 7 patients were excluded because of poor image quality.

## Group Characteristics

Group Characteristic	Controls (n=153)	Compartment Syndrome (n=11)
Age	36.1±16	36.3±17
MAP	97±16 mmHg	96±28 mmHg
Body Temperature	36.6±1.1°C	36.3±0.99 °C
Ambient Temp	23.5±0.98 °C	23.6±0.99 °C
TOA-TOI	93±58 min	91±67 min
RTS	8+/-4 (12)	7 +/-4 (4)
ISS	21+/-13 (20)	20+/-15 (16)
Intubated	67 (44%)	7 (64%)
MAP≤60mmHg	3 (2%)	1 (9%)
Systolic BP<90mmHg	4 (3%)	2 (20%)
Head Injury	78 (51%)	7 (64%)
Chest Injury	64 (42%)	5 (45%)
Abdomen/pelvis	39 (25%)	4 (36%)
LE fractures	24 (16%)	9 (82%)*

Table 1. TOA-TOI represents approximate time from injury (TOI) to time of arrival (TOA) in the Emergency Department. RTS= Revised Trauma Score mean, standard deviation and (median). ISS= Injury Severity Score mean, standard deviation and (median), Lower extremity (LE) fractures. Physiological variables are reported as the means and standard deviations while distribution of injuries are reported as totals and percentages of the total. \*Chi-Square analysis  $p<0.001$  compared with control group.

## Compartment Syndrome Outcome

<u>CS</u>	<u>Surgery</u>	<u>Injury Mechanism and pattern</u>	<u>Limb Outcome</u>
Left	20	MC, TBI, left tibia/fibula FX PTX, pulmonary contusion, liver laceration	left AKA
Left	7	MVC, left femur FX, left tibia FX, PTX, flail chest, pulmonary contusion	limp, skin necrosis
Left	6	MVC, left fibular FX left acetabular fracture	limp
Left	6	MVC, left leg contusion pulmonary contusion,	limp
Right	8	MVC, TBI, right tibia/fibula FX left femur FX, left tibia FX, pelvic FX	right AKA
Right	6	MC, TBI, right tibia/fibula FX pulmonary contusion and PTX	non healing ulcers right leg
Right	4	Assault with bat, TBI, leg contusion	functional
Bilateral	26	PVC, TBI, tibia/fibula FX (B)	severe left leg contracture
Bilateral	9	PVC, TBI, femur FX (B), PTX shock, spleen laceration	AKA (B)
Bilateral	3	Industrial crush, TBI, right femur FX	functional
Bilateral	3	Fall, tibia/fibula FX (B)	functional

Table 2. Demographics of patients that developed compartment syndrome. Surgery represents approximate time (hours) from injury to operative intervention. Abbreviations; CS (compartment syndrome), FX (fracture), PVC (pedestrian struck by a car), MVC (motor vehicle crash), MC (motorcycle crash), TBI (traumatic brain injury), PTX (pneumothorax), AKA (above the knee amputation) and (B) (bilateral).



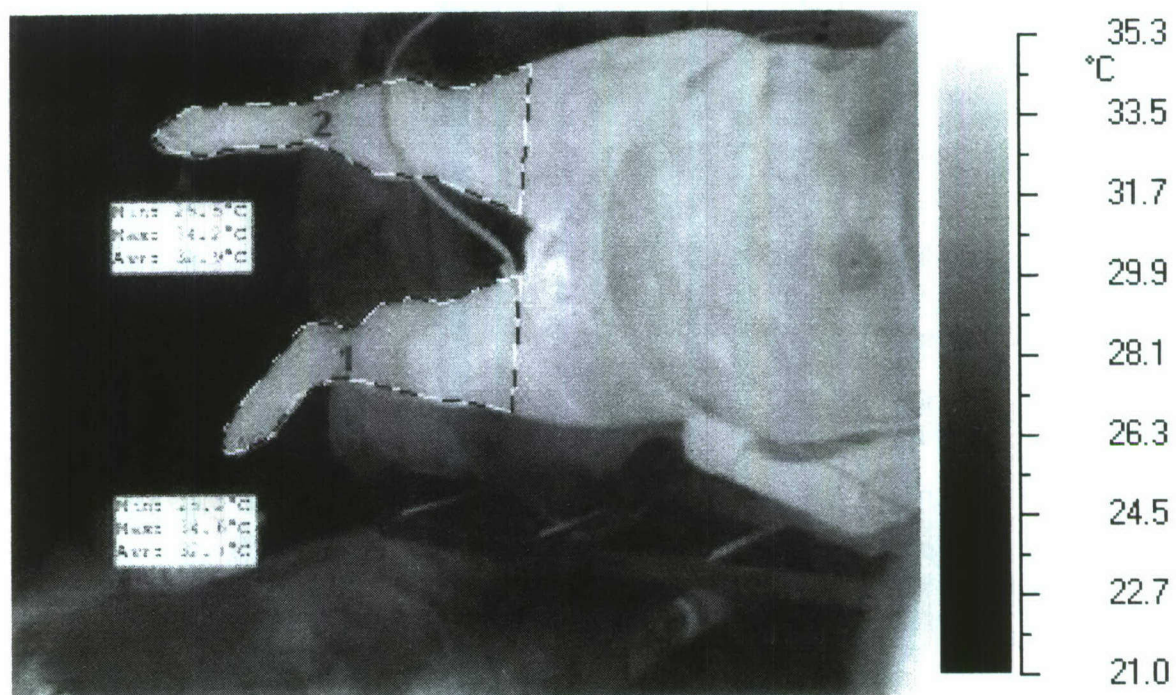


Image 1. Region of interest (entire anterior leg) outlined and analyzed by Thermography Suite in patient without compartment syndrome



Image 2. Region of interest outlines in patient with right compartment syndrome.

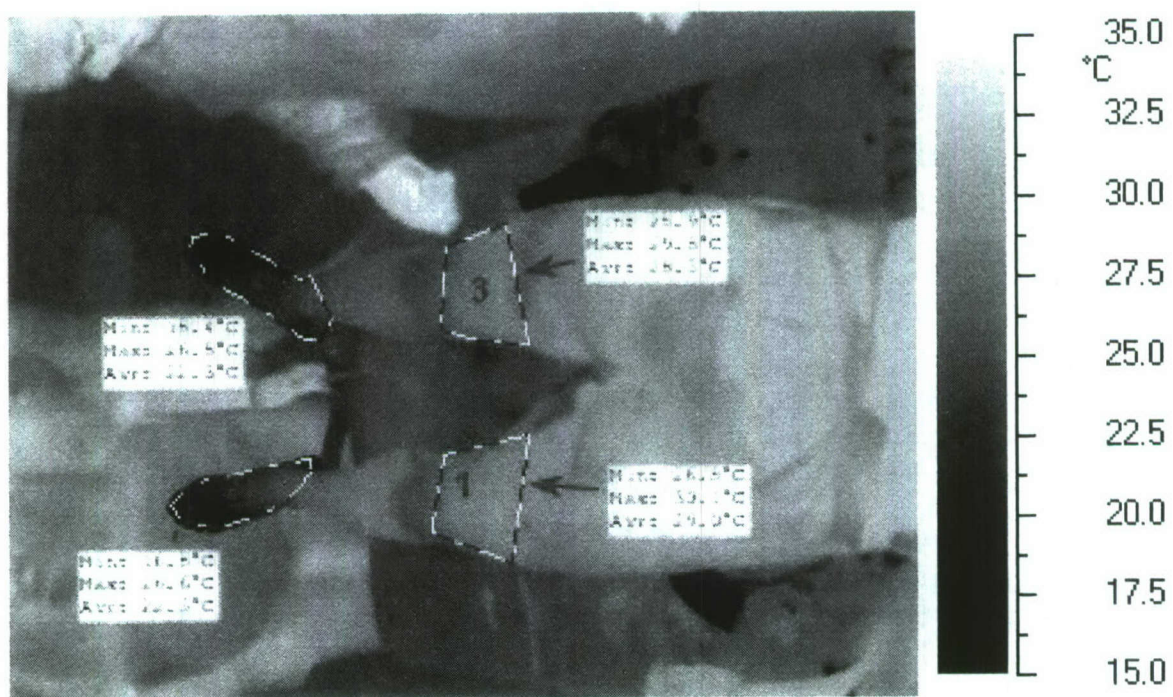


Image 3. Region of interest (anterior thigh-foot index) outlined in a trauma patient with bilateral compartment syndrome.



## Logistic Fit of Compartment Syndrome Diagnosis by Thigh-Foot Index (TFI)

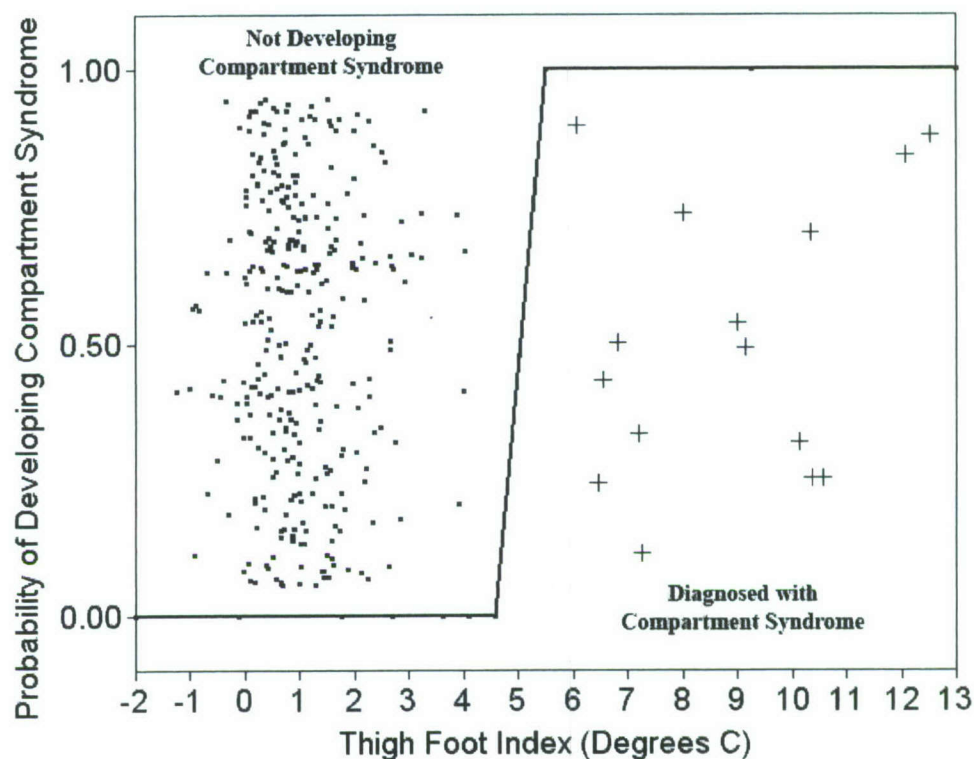


Figure 1. The figure shows the maximum likelihood probability curve (solid line) for the compartment syndrome diagnosis derived from fitting the Thigh-Foot Index (TFI) data to a nominal logistics model. TFI is the average temperature of the anterior thigh surface minus the average temperature of the anterior foot. The Y axis represents the likelihood ratio (0-1) of the diagnosis of compartment syndrome and applies only to the probability curve, not to the scatterplot points. Scatter points designated with dots (·) indicate TFI measurements for which compartment syndrome was not observed; points designated with crosses (+) denote TFI measurements for which a diagnosis of compartment syndrome occurred. Scatter plot of the TFI observed in the legs that develop compartment syndrome are all below the logistics fit line, completely discriminated from the TFI found in the legs that do not develop compartment syndrome.